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ATMOSPHERIC CONDITIONS ASSOCIATED WITH A TORNADO AT THE END OF SOUTHWEST MONSOON 2001 IN BANGLADESH – A CASE STUDY

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ABSTRACT

An attempt has been taken to study the meteorological conditions associated with the severe thunderstorm/ tornado, which occurred near the rivers Jamuneswary and Teesta at Nilphamari and Lalmanirhat on 5 October 2001. The synoptic surface and upper air circulations were favourable for a thunderstorm to occur with moderately heavy to heavy rainfall over Rajshahi division. The instability indices of the troposphere, except Showalter Index, were favourable for the occurrence of moderate to severe thunderstorm with tornadic intensity. The level of Wet-bulb Zero, the freezing level and Lifted Condensation Level descended significantly on 5 October in comparison to 3-4 October, which were favourable for thunderstorm. Satellite cloud imageries showed the cloud patterns of a well-marked low. There was a well-organized circulation patterns of bright cloud up to 18:32 BST on 4 October 2001. This bright cloud mass (Cb-cloud) was responsible for the occurrence of the severe thunderstorm with marginal tornadic intensity. The updraft was about 50-55 ms^{-1} in the convective cloud. The surface moisture over the Rajshahi division was maximum with about 97% of moisture and the precipitable water content of the troposphere was 50-60 mm over northwest Bangladesh, which was favourable for showery type weather with thunderstorm. The rainfall retrieved from TRMM and the actual observed rainfall on 5 October 2001are in well agreement.

1. INTRODUCTION

For the peculiar geographical condition of Bangladesh with the Bay of Bengal to the south and Himalayan ranges to the north, severe thunderstorms occur in different parts of the country during the pre-monsoon season (March–May). Due to the apparent position of the sun the soil in this region of Bangladesh and adjoining countries gets heated and the air near the surface of the earth rises up. As a result a low pressure develops over Bihar, West Bengal of India and adjoining Bangladesh. Moist and warm air from Bay of Bengal moves towards the centre of the low pressure and at the same time cold and dry air comes from the north/north-west for which a significant instability grows in the atmosphere. Because of these meteorological conditions and circulation in the atmosphere strong cumulonimbus cloud forms and severe thunderstorm occurs. During pre-monsoon season most of the thunderstorms proceed from the northwest direction and as such they are known as nor'westers in Bangladesh and adjoining Indian states. When the instability of the atmosphere is very significant, a portion of the thunderstorm cloud descends as a pendant reaching near the surface of the earth like a funnel cloud or elephant trunk, which has severe twisting effects. This type of cloud is known tornado. Almost every year one or two tornadoes occur in Bangladesh during the pre-monsoon season (Hosen and Jubayer, 2016). Generally, nor'westers move nearly in straight path but tornado moves in zigzag path. The damaging effect of tornado differs greatly from nor'wester. At the end of the southwest monsoon season in Bangladesh during the first quarter of the month of October instability also grows in the atmosphere due to the interaction of the warm and moist air from the Bay of Bengal and relatively cold and dry air from the north and sometimes thunderstorm forms over Bangladesh. Sometimes severe thunderstorm with tornadic intensity occurs in some parts of the country at the end period of the southwest monsoon season.

During the pre-monsoon season the energy associated with a tornado is released mainly in the form of damaging effect, and relatively less rainfall occurs. But during the end of the southwest monsoon, the energy associated with severe thunderstorm with tornadic intensity is released in the form of less damaging effect and heavy rainfall occurs during this time. It is mentioned that all the thunderstorms/tornadoes are locally developed and are known as local severe storms.

A number of investigations have been made on severe thunderstorms of the pre-monsoon season by Researchers in India. Rai Sircar (1953) made a study on the use of Tephigrams for forecasting of thunderstorms/nor'westers and obtained favourable conditions especially instability and moisture conditions for the occurrence of nor'westers. Koteswaram and Srinivason (1958) have shown in their study that the nor'westers fails to occur in

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the Gangetic West Bengal and Assam in the absence of southerly winds up to at least 3000 ft (1 km) in spite of the other conditions being fulfilled. Sen and Sengupta (1961), De and Sen (1961), Nandi and Mukherjee (1966), Mukherjee and Bhatcharya (1972) and Mukherjee *et al*. (1977) made studies on different aspects related to the favouraable conditions for the formation, structure, time of occurrence and devastations of nor'westers and obtained important results. Nandi and Mukherjee (1966) mentioned that the Cooch Behar tornado on 19 April 1963 moved about 75 kph to the east-southeast. Kumar (1972) made a study of pre-monsoon thunderstorm/dust storm activity over Delhi and neighbourhood. The frequencies of occurrence of thunderstorms/dust storms were found to be 50 and 48% when the Showalter stability index ranges are <-4 and 2 to –4, respectively. The frequency of occurrence is 77% when the convective condensation level (CCL) is 800 hPa. When the mean mixing ratio (gm/kg) ranges at 850, 800 and 700 hPa are 7.12 to 10.5 and > 10.5, the frequencies of occurrence were 43 and 63%, respectively. Chowdhury and Karmakar (1986) studied the characteristics of nor'westers over Bangladesh and found that sufficient heating and instability of the atmosphere up to 500 hPa were required and the places of occurrence fell within or near the area of maximum dew-point depression prior to the occurrence. Das *et al*. (1994) studied the different meteorological conditions associated with 5 severe thunderstorms occurred in Bangladesh. According to them the crossing point of the axes of low level (850 hPa) maximum wind and upper level jet stream appears to give a unique indication of the places of occurrence of local severe storms. Akram and Karmakar (1998) studied some meteorological aspects of the Saturia tornado, 1989. According to them, the tornado was found to occur near the point of intersection of the axes of the moist and dry zones at the surface about 6 hours before the occurrence. Recently, a number of studies have been studied by Karmakar (2001, 2005), Karmakar and Alam (2005, 2006, 2007a, 2007b, 2007c, 2011, 2015a, 2015b, 2017), Karmakar and Mannan (2014), Karmakar and Quadir (2014, 2015), Das *et al. (*2015a, 2015b, 2017a, 2017b), Karmakar and Das (2017) and Karmakar *et al.* (2017) on the atmospheric conditions associated with nor'westers/ thunderstorms/tornado and their simulations. These studies are related to the thunderstorms and tornadoes which occurred during the pre-monsoon season.

Karmakar and Imam (2016) made a diagnostic study on the meteorological conditions associated with tornadoes in Bangladesh. They found that 24-hr pressure change over Bangladesh in case of Kalihati tornado on 13 May 1996 started falling since the morning especially over the northwestern part of Bangladesh, having the value of –6.0 hPa over Syedpur-Rangpur-Dinajpur-Bogra region with its trough extending to Tangail-Dhaka region at almost all the observation times. The low-level circulation up to 10,000 ft and the upper air westerly jet stream with its trough were favourable for Saturia and Kalihati tornadoes. The spatial distribution of minimum temperature over Bangladesh indicated intrusion of warm air through the southwestern part of the country up to Dhaka division and presence of cold air just northwest of Dhaka in both the cases. This reveals that there was an interaction of cold and warm air over place of occurrence of the tornadoes. The tornadoes occurred near the point of inter-section of the dry and moist zones as revealed by the distribution of relative humidity over Bangladesh.

Generally, thunderstorm of tornadic intensity does not occur at the end of the southwest monsoon season in Bangladesh and so, studies are not available for monsoon tornado in the country. This paper is an attempt to study the different meteorological conditions associated with the severe thunderstorm with marginal tornadic intensity, which occurred at Nilphamari and Lalmonirhat of Bangladesh on October 5, 2001.

2. DATA USED

Surface data on 3-hourly pressure, relative humidity, TRMM rainfall, BMD rainfall, synoptic surface and upper air charts and change charts of different parameters have been taken from Bangladesh Meteorological Department (BMD) and rawinsonde data at different stations obtained from BMD and Wyoming University during 3-6 October 2001 has been utilized in this study. The rawinsonde stations are shown in Figure 1a.

The European Centre for Medium-Range Weather Forecasts (ECMWF) product ERA-interim is used for studying large scale flow patterns and mean sea level pressure distribution associated with the tornadic event on 5 October 2001. These are reanalysis products, which have superseded the ECMWF Climate data Assimilation System (ECDAS). After increasing computational power, a new state-of-the art technique four dimensional variational assimilation (4D-Var) is applied to improve data quality. The computational improvement has inspired to make data resolution from T159 (N80, nominally 1.125 degrees for ERA-40) to T255 (N128, nominally 0.703125 degrees). In addition, data assimilation of ERA-Interim also benefits from quality control that draws on experience from ERA-40 and JRA-25, variational bias correction of satellite radiance data, and more extensive use of radiances with an improved fast radiative transfer model. The data sets contain 60 model levels and the maximum is 0.1 hPa (Dee *et al.,* 2011).

3. METHODOLOGY

Mean sea level pressure, surface and upper air circulation charts were prepared from the ERA data; mean sea level pressure recorded by BMD was also used to have its spatial distribution over Bangladesh. These charts were critically discussed to obtain the synoptic and upper air conditions associated with the event. Satellite cloud imageries were used to detect the bright cloud structure. 3-hourly pressure was used to see the diurnal variation of mean sea level pressure at Dinajpur, Syedpur and Rangpur, which were near the place of occurrence of the tornado event. Relative humidity was distributed spatially over Bangladesh to see the availability of moisture near the place of occurrence of the event. Temporal variation of rainfall recorded by BMD at Rangpur, Dinajpur, Syedpur and Rajshahi were studied to study the maximum rainfall near the place of occurrence of the event. BMD rainfall and TRMM rainfall were compared through its spatial distribution. Rawinsonde data were used to study the different instability indices, LCl and their spatial distribution over Bangladesh and surrounding Indian stations. All the results were discussed critically and conclusions were drawn.

4. DESCRIPTION OF THE TORNADO AND SATELLITE OBSERVATION

4.1 Description

The severe thunderstorm of 5 October 2001 moved from southwest direction towards northeast. It hit the regions of Lalmonirhat and Nilphamari at about 13:30 BST. It was associated with a nearly funnel cloud as reported by the people of the area. No trees or any other things were burnt and no pieces of tin penetrated any tree parallel to the ground. Some isolated tins from the roofs of 10ft high house were blown off on trees of about 30ft high at a distance of about 250ft. The upper part of tube well was blown off but no pipe was twisted up. It was reported that tins of some houses were twisted as per the report of the visiting Meteorologist (Shamim, 10-10-2001).

The storm descended up to 3-4ft above the ground as a funnel cloud. The length of the path was about 25 km and breadth was about 100 m. The storm after passing the Jamuneswary river of Kishoreganj Upazila became active; it was less active while passing over Gangachara of Rangpur and became active again after passing over the river Teesta. The storm destroyed a pucca road of about 3-4 ft high. The wind speed associated with the storm was estimated to be 120 km/hr or slightly more. This indicates that the storm was a severe thunderstorm with marginal tornadic intensity. The storm killed 11 people and injured about 350 people seriously (ETV News on 07-10-2001). About 10,000 kutcha and pucca houses were ravaged to the ground (The Janakantha on 06-10-2001). Kaliganj Upazila of Lalmanirhat district and Kishoreganj Upazila of Nilphamari district were severely damaged. The storm lasted for about 30 seconds at Kishoreganj.

4.2 Satellite observation

Analysis of satellite imagery showed well organized circulation patterns of cloud up to 18:32 BST on 4 October 2001. But at 00:32 BST on 5 October, the circulation is seen to weaken and it remained almost the same up to 03:32 BST. This system indicated possibility of heavy rainfall over Rajshahi Division and other places too. But the system began to intensify again from 10:25 BST on 5 October and a bright cloud mass (Cb-cloud) appeared at 12:32 BST on the same day. This bright cloud mass (Cb-cloud) was responsible for the occurrence of severe thunderstorm with marginal tornadic intensity.

5. RESULTS AND DISCUSSION

5.1 Synoptic surface and upper-air conditions

A well-marked low developed over the West Central Bay of Bengal and adjoining South Bay of Bengal on 29 September 2001 and it crossed Indian coast on 30 September. Then it was moving slowly towards northwest over eastern Madhya Pradesh and adjoining area giving moderately heavy to heavy rainfall over Bangladesh and adjoining area. Bangladesh Meteorological Department issued rainfall forecast for 24 hrs and subsequent two days accordingly. During 1-3 October, the well-marked low weakened into a low and moved over Eastern Uttar Pradesh and adjoining Bihar of India, fell into the westerly system and began to move slowly in a north easterly direction. Because of the presence of the low, there was steep pressure gradient over Dinajpur, Rangpur and Syedpur with a prominent trough extending to east-northeast direction up to Mymensingh region (not shown in figure for brevity). Figure 1b shows the position of well-marked low over eastern Uttar Pradesh and adjoining Bihar with its trough extended eastwards to northwest Bangladesh. The trough was prominent over northwest Bangladesh and the pressure was found much lower at 0900 UTC as compared to that at 0000 UTC (Figure 1c).

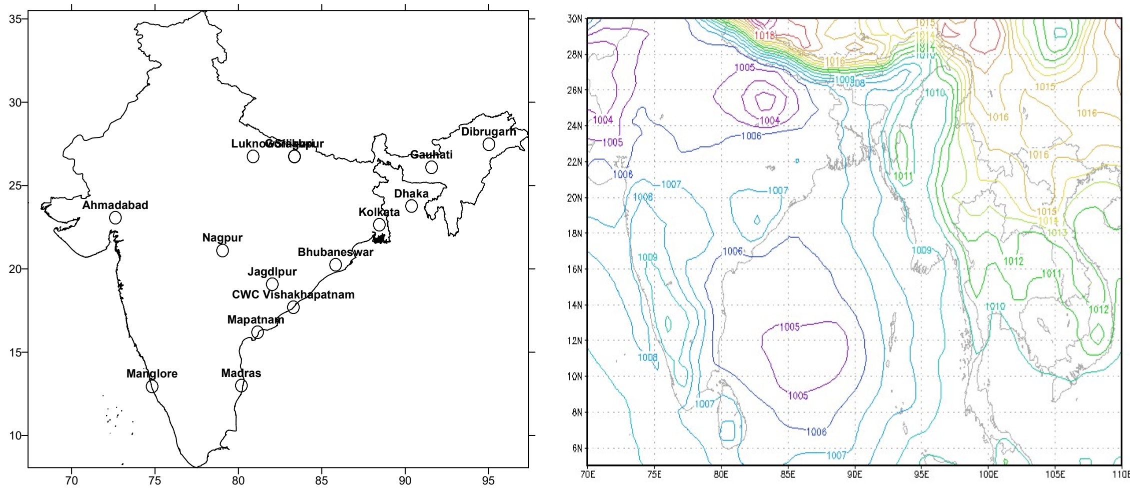

Figure 1: a) Location of Rawinsonde Stations and b) Spatial distribution of mean sea level pressure obtained from ERA data at 0000 UTC on 5 October 2001

The circulation patterns at 850 hPa and these wind fields are obtained from the NWP products of Bracknell and the diagrams prepared from ERA data. It has been found that the movement of the well-marked low is towards northwest and then towards northeast. The circulation has been found to extend up to 700 hPa. The movement of the low towards northeast is due to the upper air westerly current [Figs. 2(a-c)]. Figure 2a shows the circulation over the well-marked low at the surface (i.e. at 925 hPa) and is more prominent at 850 hPa level as can be seen in Figure2b. Figure 2c shows the westerly flow over eastern Uttar Pradesh, Bihar, sub-Himalayan West Bengal and adjoining Bangladesh and this westerly flow was responsible for the east-northeast movement of the well-marked low.

On the basis of the movement of the low pressure system, Bangladesh Meteorological Department issued 24 hours weather forecast on 4 October for rain/thunder shower at many places of Rajshahi division with moderately heavy to heavy falls at one or two places over Rajshahi, Dhaka and Chittagong divisions during the following 24 hours.

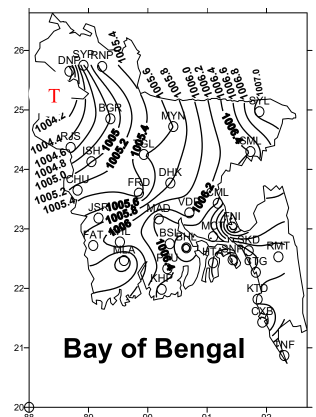

Figure 1c: Spatial distribution of mean sea level pressure at 0900 UTC on 5 October 2001 (Source: BMD)

5.2 Diurnal variation of mean sea level pressure over Bangladesh

The diurnal variations of mean sea level pressure at Dinajpur, Rangpur and Syedpur are shown in Figures 3(a-c), respectively. All the figures show increase of pressure from 0000 UTC to 0300 UTC over there and then starts decreasing achieving the lowest pressure at about 0930 UTC, 0945 UTC and 1045 UTC at Dinajpur, Rangpur and Syedpur, respectively. This time of attaining of lowest pressure indicates that the tornado occurred at around 1045 UTC, which differs with the opinion of community people at Nilphamari. The change in pressure with respect to 0300 UTC at 0900 and 1200 UTC are given in Table 1. The table indicates that maximum fall of pressure of 4.5 hPa occurred at Syedpur at around 1200 UTC and was responsible for the occurrence of tornado.

Table 1: Change in sea level pressure at different places on 5 October 2001

Stations	ΔP (hPa)	Comparative times
Dinajpur	3.7	at 0900 UTC as compared to 0300 UTC observed
Rangpur	3.5	at 0900 UTC as compared to 0300 UTC observed
Syedpur	4.5	at 1200 UTC as compared to 0300 UTC observed

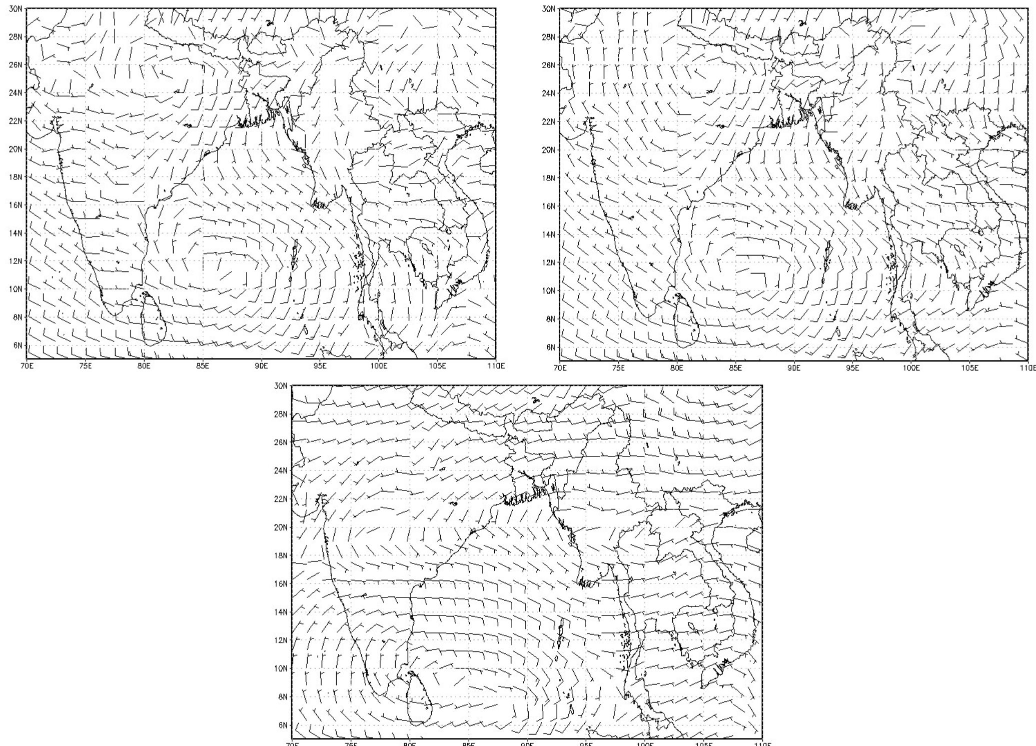

Figure 2: Circulation of a) 925, b) 850 and c) 500 hPa level at 0000 UTC on 5 October 2001 based on ERA data

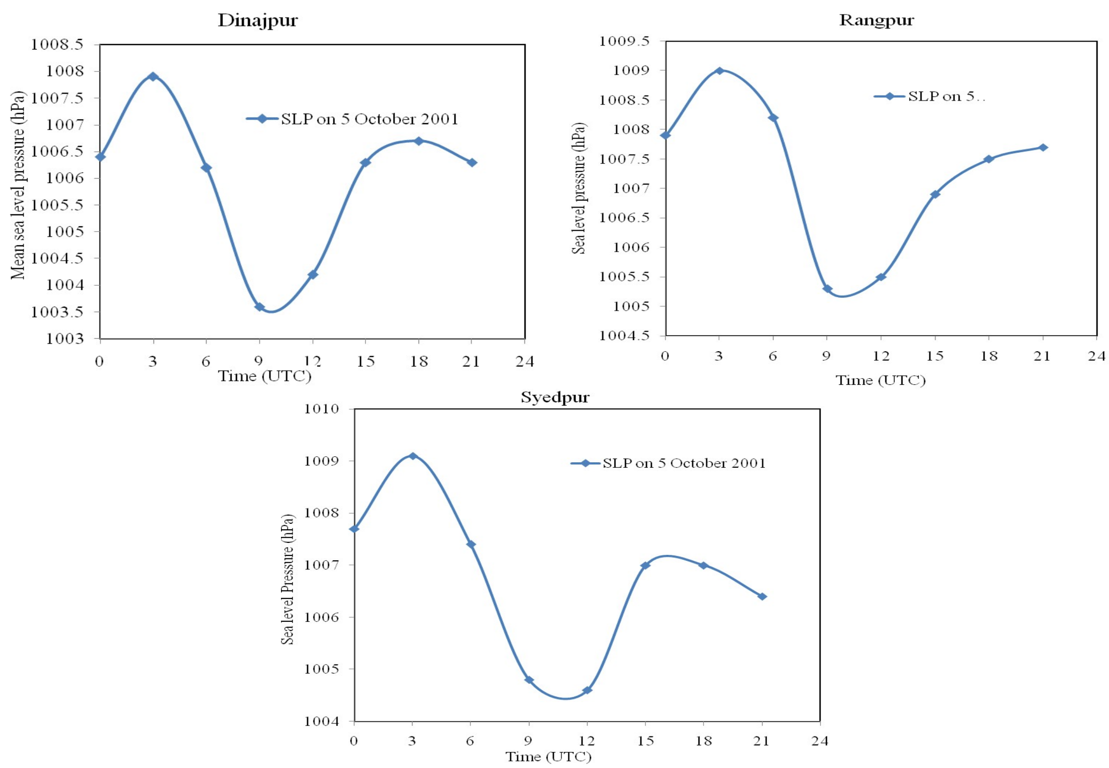

Figure 3: Diurnal variation of MSLP at a) Dinajpur, b) Rangpur and c) Syedpur on 5 October 2001

5.4 Rainfall associated with the tornado

The temporal variation of 24 hours rainfall is shown in Figure 4. The figure shows that heavy to very heavy rainfall occurred at Syedpur (237 mm), Rangpur (214 mm), and Dinajpur (94 mm) of Rajshahi division on 5

October. But at about 13:00 BST on 5 October, a severe thunderstorm with marginal tornadic intensity occurred at Lalmonirhat and Nilphamari of Rajshahi division. TRMM rainfall also ranges from 224 mm to 256 mm as can be seen from Figure 5. This amount of rainfall is comparable with the actual rainfall as can be seen from Figure 6. These figures indicate that heavy to very rainfall was associated with the tornado on 5 October 2001.

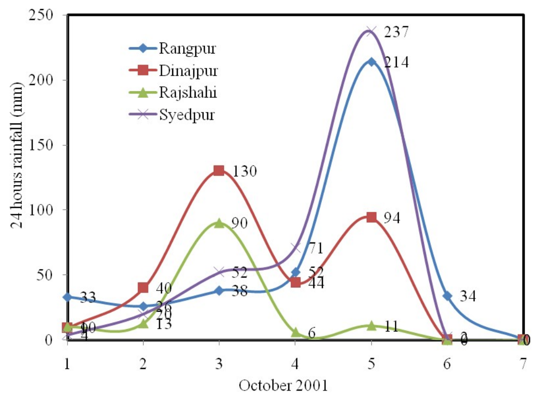

Figure 4: Temporal variation of rainfall at Rajshahi, Dinajpur, Rangpur and Syedpur during 1-7 October 2001 (Source: BMD)

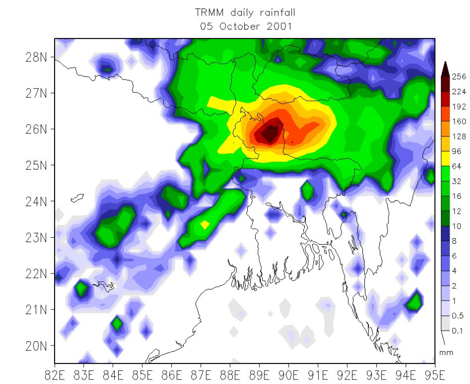

Figure 5: Distribution of 24 hours rainfall on 5 October 2001

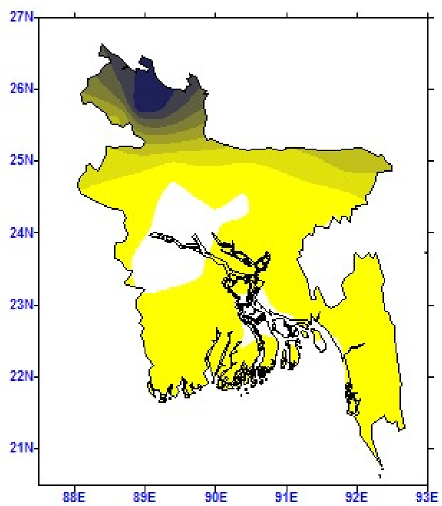

Figure 6: Spatial distribution of 24 hrs rainfall at 0900 UTC on 5 October 2001

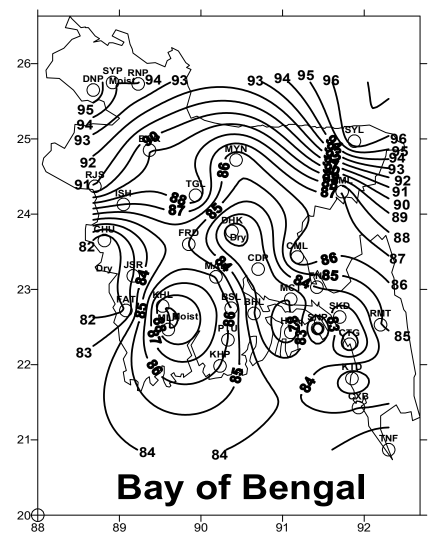

Figure 7: Spatial distribution of mean Relative Humidity (%) over Bangladesh on 5 October

5.5.1 Spatial distribution of surface moisture

The surface moisture in terms of relative humidity of 0000 UTC at all stations of Bangladesh Meteorological Department has been plotted (Figure 7) on 5 October 2001 and analyzed. It is seen from the analysis that there exists an area of maximum moisture over the Rajshahi division with about 97% of moisture on 5 October and this was favourable for showery type weather with thunderstorm. The mean relative humidity is also higher with 93-95% in northwest Bangladesh, the place of occurrence of the tornado. In the north of this area, the air was relatively drier. The interaction of warm moist over Dinajpur-Rangpur-Sayedpur and the dry air in the north was favourable for the occurrence of the tornado.

5.6 Instability of the atmosphere

5.6.1 Instability indices

Interestingly, analysis of upper air sounding at Dhaka and adjoining Indian stations on 5 October indicated that one or two parameters were favorable for thunderstorm and shower, and others were not favorable. The instability of the troposphere was determined with the help of Tephigram. The comparative results of some parameters obtained from the analysis of Tephigram at Dhaka and Kolkata are given in Table 2. It is seen from the table that the Showalter index was positive at both the stations of Dhaka and Kolkata having values 1.7 and +1.5°C on 5 October, which indicated stable atmosphere and these values indicated only showery weather. But the level of Wet-bulb Zero and the freezing level descended significantly on 5 October in comparison to 3-4 October, which indicated the favourable conditions for thunderstorm. Based on the circulation patterns in the upper air wind field, cloud pattern and the Tephigram analysis of 5 October, Bangladesh Meteorological Department issued inland river port warnings in due time.

Table 2: Comparison of instability and other thermodynamic parameters of the atmosphere at 0000 UTC during 3-5 October

Station	Parameters	October 2001		
		3	4	5
Dhaka	Showalter index (SI)	-0.56 °C	-	+1.7°C
	Wet Bulb Zero (WBZ)	560 hPa		573 hPa
	Freezing Level (FL)	550 hPa		549 hPa
	ΔSI	+1.56°C		+0.0°C*
	ΔWBZ	-18 hPa		+13 hPa*
	ΔFL	-13 hPa		-1 hPa*
Kolkata	Showalter index (SI)	0.0°C	+1.0°C	+1.5°C
	Wet Bulb Zero (WBZ)	525 hPa	590 hPa	620 hPa
	Freezing Level (FL)	513 hPa	560 hPa	574 hPa
	ΔSI	+3.0°C	+1.0°C	+0.5°C
	ΔWBZ	-30 hPa	+65 hPa	+30 hPa
	ΔFL	-45 hPa	+47 hPa	+14 hPa

*$\Delta SI = \Delta SI_{5\text{-}3\ 0ct}$, * $\Delta WBZ = \Delta WBZ_{5\text{-}3\ 0ct}$, *$\Delta FL = \Delta FL_{5\text{-}3\ 0ct}$

Spatial distributions of Lifted Index, CAPE, SWEAT Index and Total Totals Index are shown in Figures 8(a-d), respectively. Figure 8a shows that the Lifted Index over the place of occurrence ranges from -3 to -3.5°C, which indicates unstable condition with moderate-severe lifting mechanism (https://en.wikipedia.org/). Convective Available Potential Energy (CAPE) is a measure of the amount of energy available for convection. CAPE is directly related to the maximum potential vertical speed within an updraft; its higher values indicate greater potential for severe weather. Observed values in thunderstorm environments often may exceed 1,000 joules per kilogram (J/kg), and in extreme cases may exceed 5,000 J/kg (https://www.weatheronline.co.uk/). In the present case of tornado, the CAPE is found to range between 1250-1500 J/kg over the place of occurrence (Figure 8b), which is moderate and this value has the potential to uplift some objects upward, which is comparable with the actual observed damage conditions over the place. This amount of CAPE is equivalent of updraft of about 50-55 ms^{-1} according to the formula (Dutton, 1976) (http://umanitoba.ca/):

$$w_{\max} = \sqrt{2 \times CAPE}$$

It may be mentioned that CAPE is 1765.2 J/kg at Dhaka, indicating the possibility of moderate to severe thunderstorms. The SWEAT Index on this day of October 2001 is found to range 200-220 over the area (Figure 7c), indicating moderate to severe thunderstorm (Karmakar, 2005). Figure 8d shows the distribution of Total Totals Index having the range of 42-43°C over the place of occurrence, which indicates scattered thundershower to few moderate to severe thunderstorms (Karmakar, 2005).

5.6.2 Vertical profiles of equivalent potential temperature

Equivalent potential temperature, commonly referred to as theta-e (θ_e), is a quantity that is conserved during changes to an air parcel's pressure (that is, during vertical motions in the atmosphere), even if water vapor condenses during that pressure change. It is therefore more conserved than the ordinary potential temperature, which remains constant only for unsaturated vertical motions (pressure changes). θ_e is the temperature a parcel of air would reach if all the water vapor in the parcel were to condense, releasing its latent heat, and the parcel was brought adiabatically to a standard reference pressure, usually 1000 hPa, which is roughly equal to atmospheric pressure at sea level. The equivalent potential temperature has been computed for stations Dhaka, Kolkata, Gauhati and Bhubeneswar and the vertical profiles of θ_e for these stations on the dates of occurrence and the previous day are shown in Figures 9(a-d), respectively. It may be mentioned that there was no rawinsonde observation on 4 October and the data on 3, 5 and 6 October 2001 are considered for Dhaka.

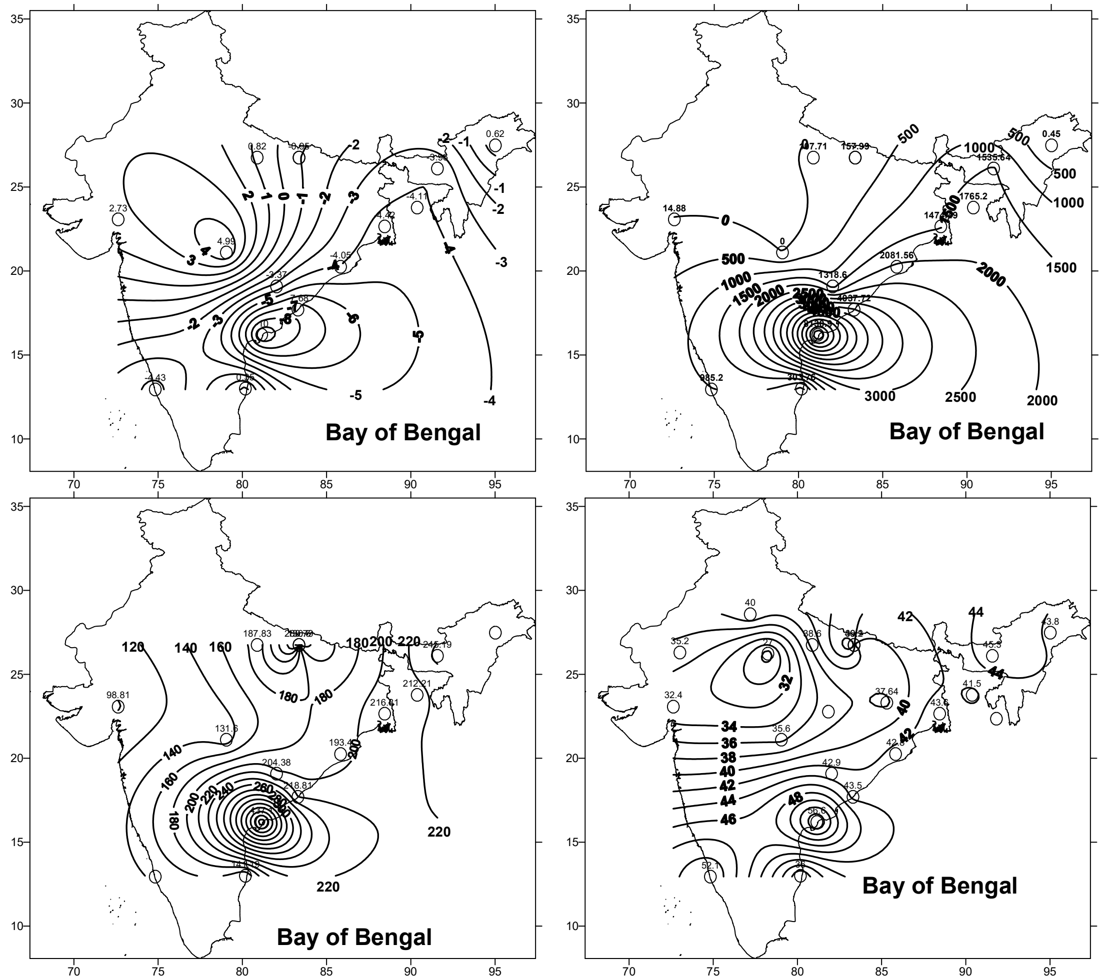

Figure 8: Spatial distribution of a) Lifted Index, b) Convective Available Potential Energy (CAPE) (Joule/kg), c) Sweat Index and d) Total Totals Index at 0000 UTC on 5 October 2001

When data of 0000 UTC is missing, data of 1200 UTC is considered. All the figures show that the θ_e decreases with height up to about 700 hPa and then increases with height. θ_e decreases from 1000 hPa to about 200 hPa level on the date of occurrence as compared to that on the previous day indicating more instability in the troposphere. The decrease in θ_e at about 700 hPa also indicates the conditional instability of the troposphere. Severe thunderstorm occurrences are preceded when a layer of the atmosphere is potentially unstable. The storm occurs when the potentially unstable is lifted to saturation (Houze, 2014). The gradients of θ_e between 1000 hPa and 500 hPa levels (or between 1000 hPa and 700 hPa) on the dates of occurrence and the previous day are given in Table 3. The table shows that the gradient of θ_e (negative values) increases on the date of occurrence, meaning to say that the convective instability increases on the date of occurrence of tornado. The lapse rates of θ_e between 1000 hPa and 700 hPa were $\frac{-19.1K}{300hPa}$ and $\frac{-26.0K}{300hPa}$ at 0000 UTC on 5 October 2001 at Dhaka and Kolkata, respectively. From simple layer concept, it is known whether a layer which may at present be stable has the potentiality to become unstable with the appropriate amount of lifting is determined by convective instability, (i.e. $\frac{\partial \theta_e}{\partial z} < 0$) (Byers, 1974). Therefore, the atmosphere on 5 October 2001 became potentially unstable and a thunder of tornadic intensity occurred in the afternoon.

Table 3: Gradient of equivalent potential temperature associated with the tornado

Stations	Gradient of θ_e between 1000 and 500 hPa (1000 and 700) levels							
	3 October 2001		4 October 2001		5 October 2001		6 October 2001	
	00Z	12Z	00Z	12Z	00Z	12Z	00Z	12Z
Dhaka	-7.2	-	-	-	-18.5 (-19.1)	-	-22.7 (-19)	-
Kolkata	-9.0	-	-	-16.4 (-20)	-21.3 (-26.0)	-	-25.2 (-22.0)	-22.2 (-19.0)
Gauhati	-	-15.4 (-16.6)	-8.5 (-8.6)	-	-4.7 (-8.0)	-	-	-8.1 (8.0)
Bhubaneswar	-	-23.4 (-15.1)	-	-24.6 (-23.7)	-25.0 (-26.5)	-	-22.3 (-21.0)	-

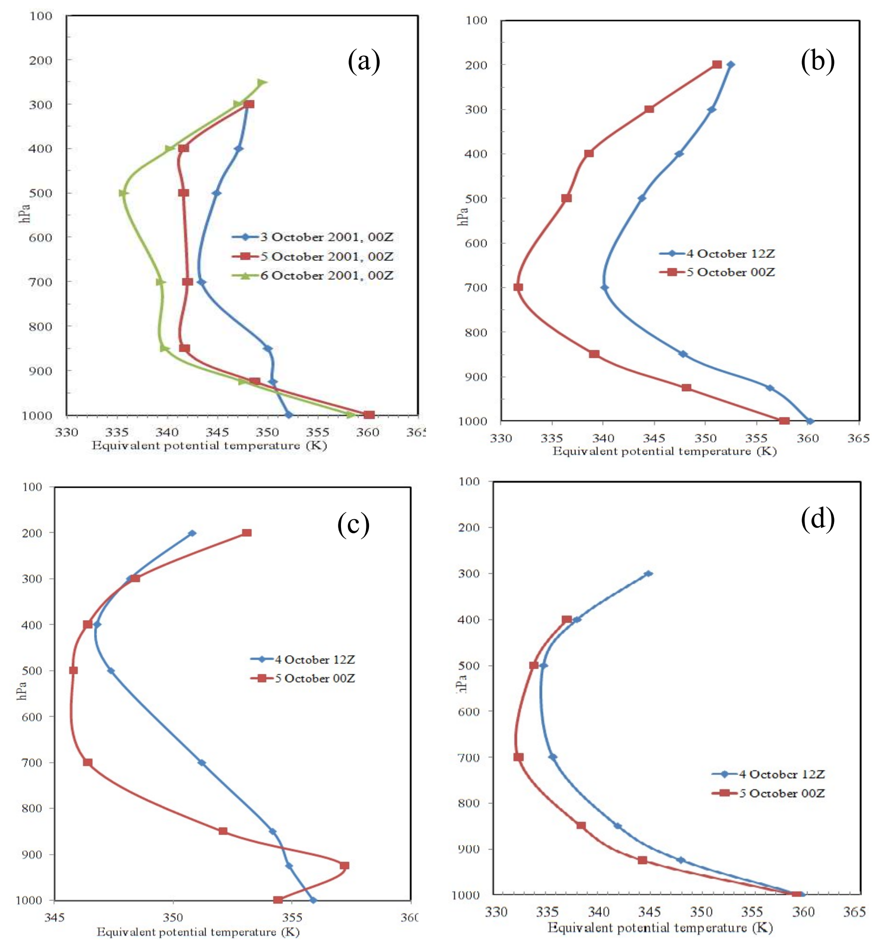

Figure 9: Vertical profile of equivalent potential temperature (K) over a) Dhaka during 3-6 October and over b) Kolkata, c) Gauhati and d) Bhubaneswar 4-5 during October 2001

5.6.3 Bulk Richardson Number

The Bulk Richardson number (BRN) is a dimensionless measure of the stability of a dynamic system. It is defined by the ratio of energy available for the vertical motion (buoyancy energy) and energy produced by vertical wind shear. Development of super cells takes place at values between 15 and 35 and that at values greater than 35 conditions are favourable for the development of multicells (Weisman and Klemp, 1982; Karmakar and Quadir, 2017). In the present case, Figure 10a shows the spatial distribution of BRN over

Bangladesh and adjoining Indian states at 0000 UTC on 5 October 2001. The figure shows the values of BRN between 300 and 400 over northwestern Bangladesh. This range of values indicates that there was strong turbulence along with super-cell cloud formation.

5.6.4 Precipitable water in the troposphere

The precipitable water content (mm) of the troposphere, collected from the data of Wyoming University web for the stations under study are spatially distributed over Bangladesh and India and is shown in Figure 10b. The figure shows that the precipitable water content of the troposphere was of the order of 50-60 mm over northwestern Bangladesh, having maximum value over northeastern part of the country and adjoining northeast India. The precipitable water content is found to decrease westward with a range of 30-40 mm over Bihar of India, indicating relatively dry air there. The interaction of dry and cold air with warm and moist air was indication of the formation of severe thunderstorm. The precipitable water content of 50-60 mm indicates severe thunderstorm with heavy shower, causing local flood (Karmakar and Quadir, 2014).

5.6.5 Cold and dry air advection near the place of occurrence

In the morning of 5 October 2001, there was cold and dry air advection near the place of occurrence of the tornado as is evident from Figures (11 and 12). Figure 10 shows that the temperature at Gorakhpur, located in the north-eastern part of the Indian state of Uttar Pradesh, is much lower than that at Dhaka throughout the troposphere and the Figure 11 shows that the atmosphere was dry from 650 hPa to 400 hPa at Gorakhpur, where the wind was northwesterly to westerly between 500 hPa and 200 hPa. This wind flow indicates that there was advection of cold and dry air from northwest to the place of occurrence of the tornado on this day (Figure 12).

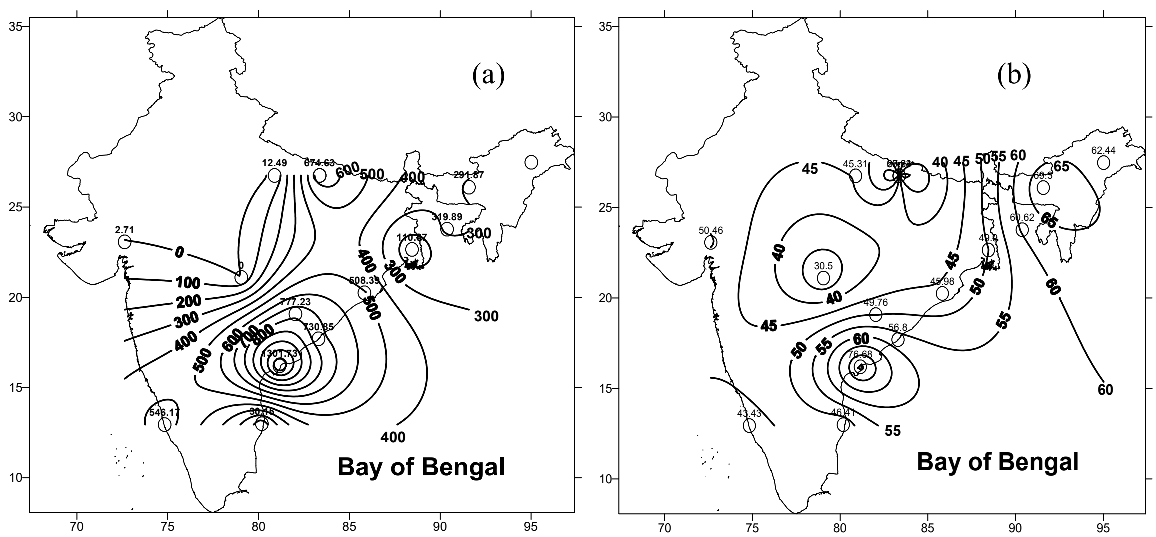

Figure 10: Spatial distribution of a) Bulk Richardson Number and b) Precipitable water (mm) at 0000 UTC on 5 October 2001

5.6.6 Lifted condensation level (LCL)

Recent research indicates a relationship between tornadic super cells and relatively high boundary layer relative humidity, which can be represented by low lifted condensation levels (LCL). Rasmussen and Blanchard (1998) found that the parameter that showed the most utility for discriminating between significant tornadoes and super-cells with either weak or no tornadoes was the height of the LCL. The median LCL height was ~ 500 m lower for the strong or violent tornado cases. Almost identical results were found by Edwards and Thompson (2000), with a mean difference in LCL height for significant tornadic versus weak or non-tornadic super cells of ~ 500 m. In the present case, spatial distribution of LCL over Bangladesh and Indian states is shown in Figure 13, which shows that the LCL is between 960 hPa and 965 hPa near the place of occurrence at 0000 UTC on 5 October 2001. This value indicates comparatively lower height with respect the surroundings, i.e. descending of LCL occurred. Table 4 shows the descending of the LCL on the date of occurrence by 11.6 hPa and 16.16 hPa at Dhaka and Kolkata, respectively and these values are equivalent to 96.54 m and 134.49 m at 15° C standard atmospheres. If we consider four stations (Figure 14) along the same longitude, the meridional variation of LCL shows that LCL increases in terms of hPa from south towards the place of occurrence in the north, indicating the descending of LCL in the north near the place of occurrence.

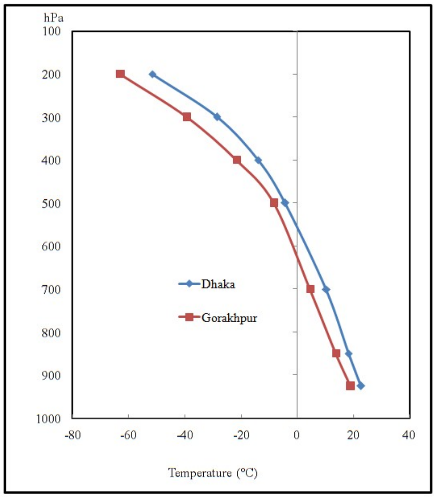

Figure 11: Comparison of temperature (°C) at Dhaka and Gorakhpur at 0000 UTC on 5 October

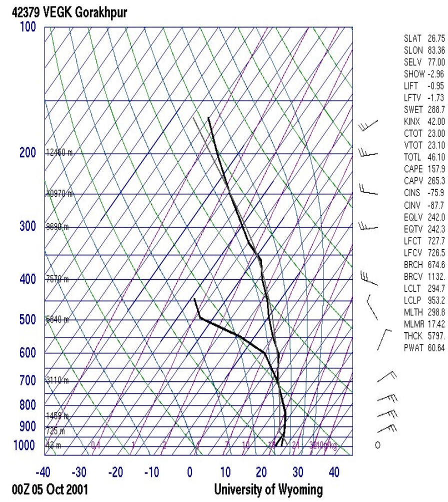

Figure 12: Skew-T diagram at Gorakhpur at 0000 UTC on 5 October 2001

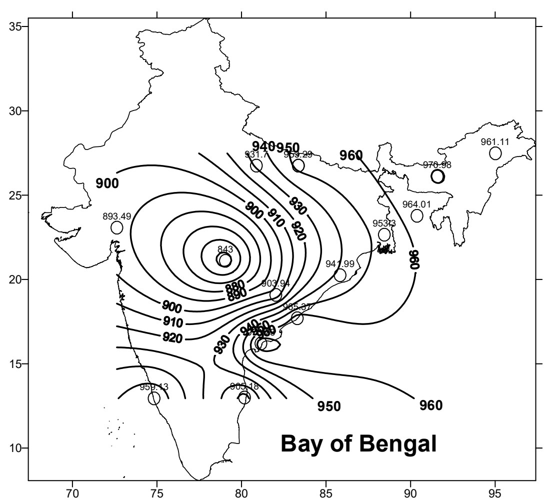

Figure 13: Spatial distribution of LCL at 0000 UTC on 5 October 2001

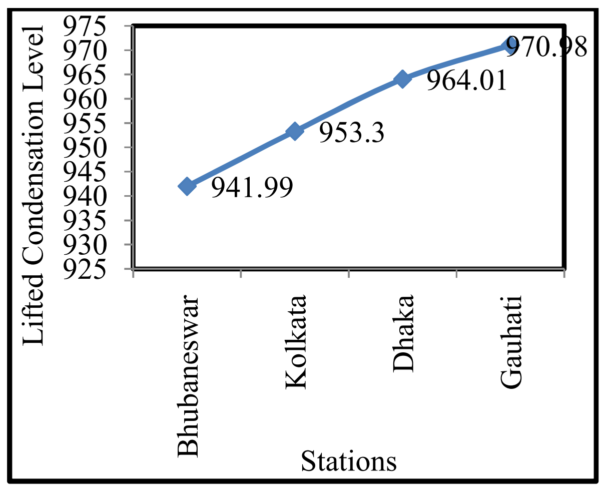

Figure 14: Meridional variation of LCL (hPa) on 5 October 2001

Table 4: Comparison of LCL on the date of occurrence with LCL on the previous day

Stations	Dates	LCL (hPa)	Δ (LCL)	ΔLCL (m) at 15° C
Dhaka	3 October 2001	952.41	11.6 hPa	96.54
	5 October 2001	964.01		
Kolkata	4 October 2001	937.14	16.16 hPa	134.49
	5 October 2001	953.30		
Gauhati	4 October 2001	966.03	4.95 hPa	41.20
	5 October 2001	970.98		

6. CONCLUSIONS

On the basis of the present study the following conclusions can be drawn:

i) The severe thunderstorm/tornado occurred near the rivers Jamuneswary and Teesta. The synoptic surface and upper air circulations with trough extended to eastward up to northwest Bangladesh were favourable for a thunderstorm to occur with moderately heavy to heavy rainfall over Rajshahi division. The westerly wind at 500 hPa level was responsible for the east-northeast movement of the well-marked low.

ii) Satellite cloud imageries showed a well-organized circulation patterns of cloud up to 18:32 BST on 4 October 2001. This bright cloud mass (Cb-cloud) was responsible for the occurrence of severe thunderstorm with marginal tornadic intensity.

iii) The mean sea level pressure was found to decrease by 4.5 hPa at 1200 UTC at Syedpur with respect to that at 0300 UTC.

iii) The analysis of upper air soundings at Dhaka and Kolkata on 5 October indicated that Showlter Index was slightly positive, which was favorable for thunderstorm and shower. The other indices such as Lifted Index, SWEAT Index, CAPE and TTI at 0000 UTC over northwest Bangladesh and adjoining Indian states were favourable for the occurrence of a moderate to severe thunderstorm of slightly tornadic intensity.

iv) The level of Wet-bulb Zero, freezing level and LCL descended significantly on 5 October in comparison to 3-4 October, which were favourable for thunderstorms. The meridional variation of LCL indicated the lowering of the LCL in the northwest part of Bangladesh.

v) There was convergence of warm moist air in the lower level and dry and cold air advection in the mid-troposphere. The updraft in the convective cloud was equivalent to 50-55 ms^{-1}, indicating the embedded tornado cloud.

vi) The equivalent potential temperature over Dhaka, Kolkata, Gauhati and Bhubaneswar was found to decrease with height up to about 700 hPa and then increase with height. The decrease in equivalent potential temperature indicates the potential instability of the troposphere, which is very favourable for the occurrence of severe thunderstorm of tornadic intensity.

vii) The equivalent potential temperature over Dhaka, Kolkata, Gauhati and Bhubaneswar was found to be less on the date of occurrence of the tornado as compared to that on the previous day.

viii) There was an area of maximum moisture over the Rajshahi division with about 97% of moisture and this was favourable for showery type weather with thunderstorm. The precipitable water content of the troposphere was of the order of 50-60 mm over northwest Bangladesh, indicating heavy to very heavy rainfall over there.

ix) Actual rainfall and TRRMM rainfall were comparable and was heavy to very heavy rainfall over northwest part of the country.

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